

Failure-mode Metrology using Projected Target videogrammetry



Coordinate Measurement System Committee
14 - 17 August 2001

By John Greenwood¹

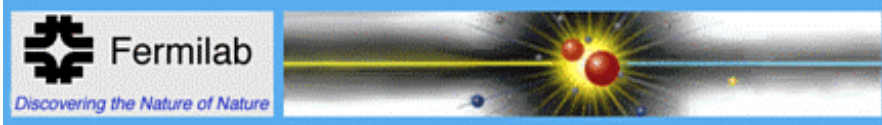
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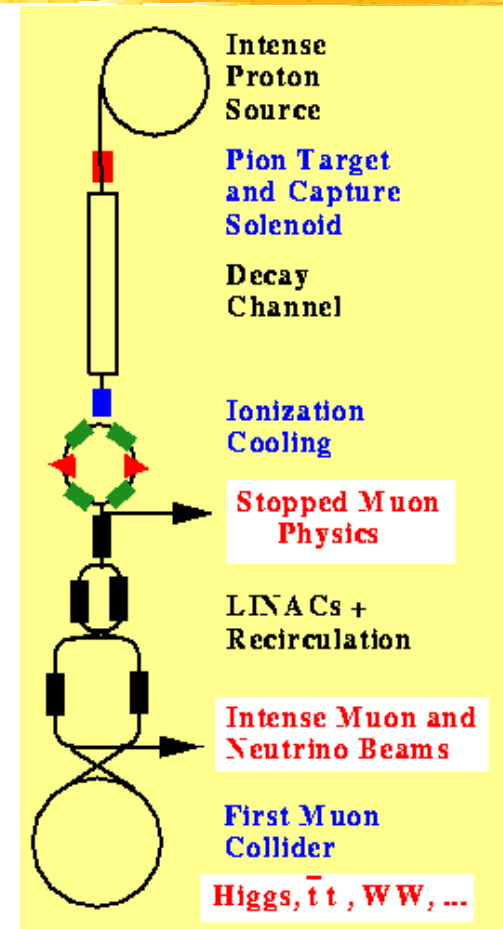


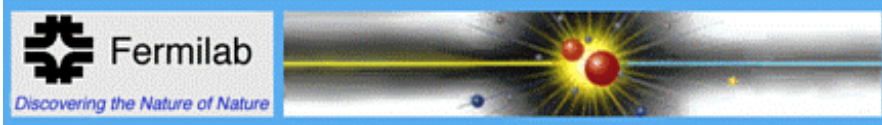
Toward the next generation of sub-atomic particle?

A Muon Collider!

Schematic of a proposed muon-based Collider

- Future particle accelerators are being researched today. One such machine is the Muon Collider under study at Fermi National Accelerator Laboratory and in several other international High-Energy Physics laboratories.

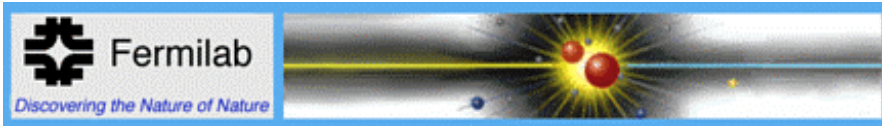




Physics issues

What is a Muon and where do Muons come from?

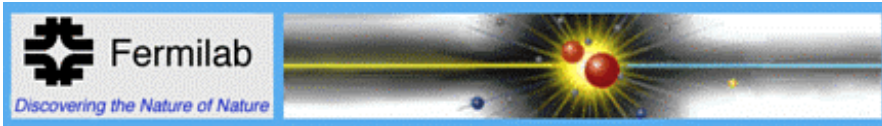
Like the electron, the muon belongs to the family of the leptons. **The muon mass is equal to 1.86×10^{-34} kg.** It has a mass ~210 times heavier than the electron, hence it possesses a larger energy. Being **more energetic** makes it a good candidate for searching for fundamental particles. It is produced by a proton interacting with a target containing liquid (with a high atomic number, Z) producing the couple **pion+ and pion-** that decay into muon+, muon-. Muons decay into **neutrino and electron**.



Physics issues

What is a Muon Collider?

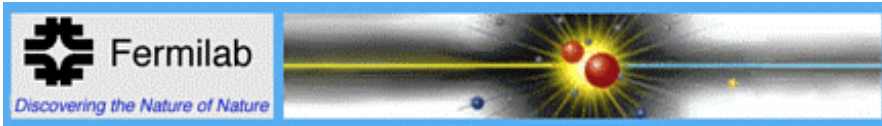
The Muon Collider is composed of a **proton source**, a target, lithium absorber, a **Linac** (Linear Accelerator made up of RF cavities, solenoids and **LH₂ absorbers**) and a storing ring with collider. The muon beam is created by a proton source being accelerated through a Linac; it releases its energy by ionization cooling along the **cooling channel** in the LH₂ absorbers. The collider is a region of the machine where the actual collisions of the muons and their antimatter partners take place, and where the products of the collisions are detected. The purpose behind colliding muons is linked to the search of the **Higgs Boson**. The second purpose of the muon collider is to provide **muon storage** in order to direct the neutrino issued from the muon decay, toward various worldwide detectors in the process of understanding the **neutrino oscillations**.



Physics issues

What do you get when you collide muons?"

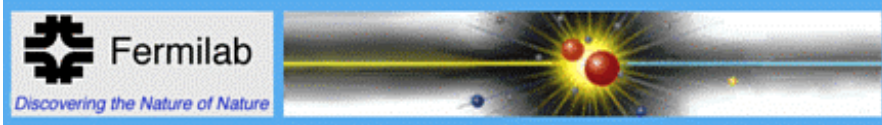
Different kinds of **elementary particles** (quarks, fermions, bosons..) will be issued from the collisions, dependent upon the **energy at the center of mass** of the two muon beams.



Physics issues

Why do you cool Muons and, maybe more importantly, how do you cool them?

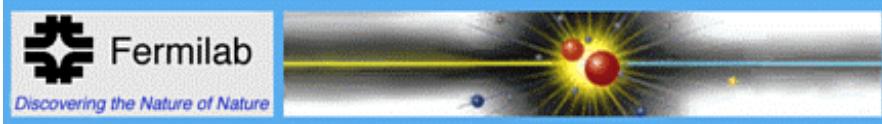
In order to operate the muon beam in proper conditions, the **phase-space volume** occupied by the initial beam needs to be reduced. The proposed technique of **ionization cooling** expects to reduce it **by a factor 10^5 - 10^6** . For this purpose, liquid hydrogen (**LH_2**) absorbers are chosen and inserted in the muon collider cooling channel. The beam needs to depose its energy (**dE/dx**) in the LH_2 absorber. The muons traverse the hydrogen volume in which they lose both **longitudinal and transverse momentum** by ionization losses. The longitudinal momentum is replaced by using the RF accelerating cavities and the solenoid magnets.



Physics issues

Why use liquid hydrogen?

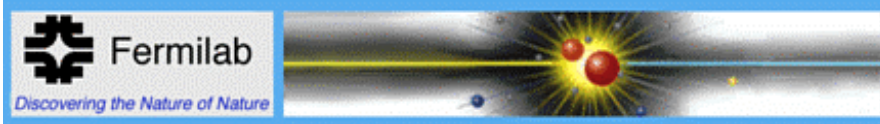
Because Hydrogen has a very **low atomic number** and the usefulness diminishes as the square of the atomic number. Helium, for example, has an atomic number of 2, while Hydrogen's atomic number is 1, which makes Hydrogen four times more effective than Helium.



Physics issues

How is the absorber window fabricated and why so thin?

The Absorber Window is made by **turning** aluminum stock on a lathe. The 20-mm diameter circle at the center of the dome is thinner than the edges. It is thin in order to **minimize losses** when the beam passes through the aluminum. One might ask why not use **Beryllium**, which has some better material properties? The answer is that Beryllium is very hazardous, and if the liquid Hydrogen should explode, the Beryllium particles would create a very severe situation. For more information.



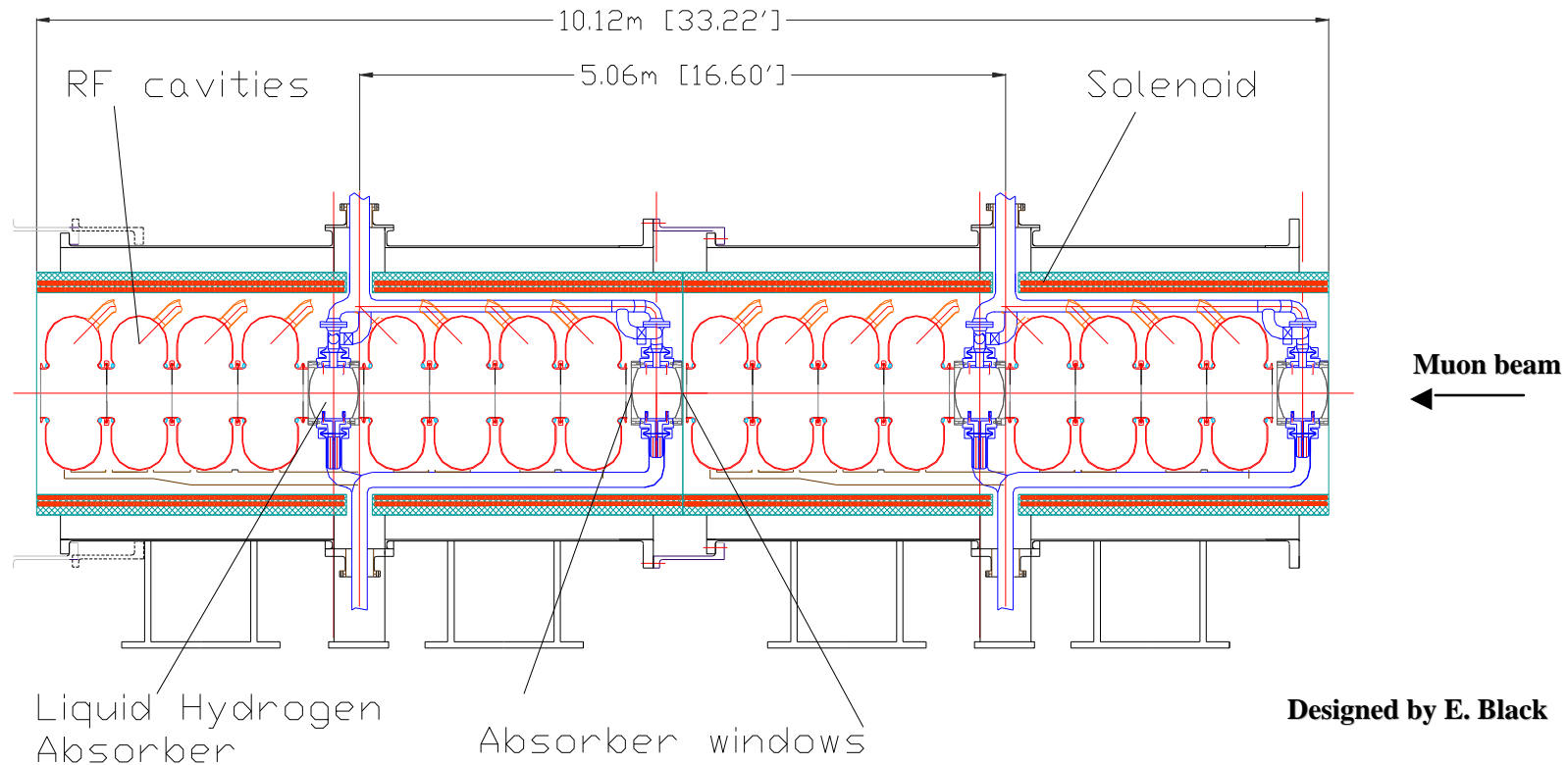
Physics issues

Why the test needs to be destructive?

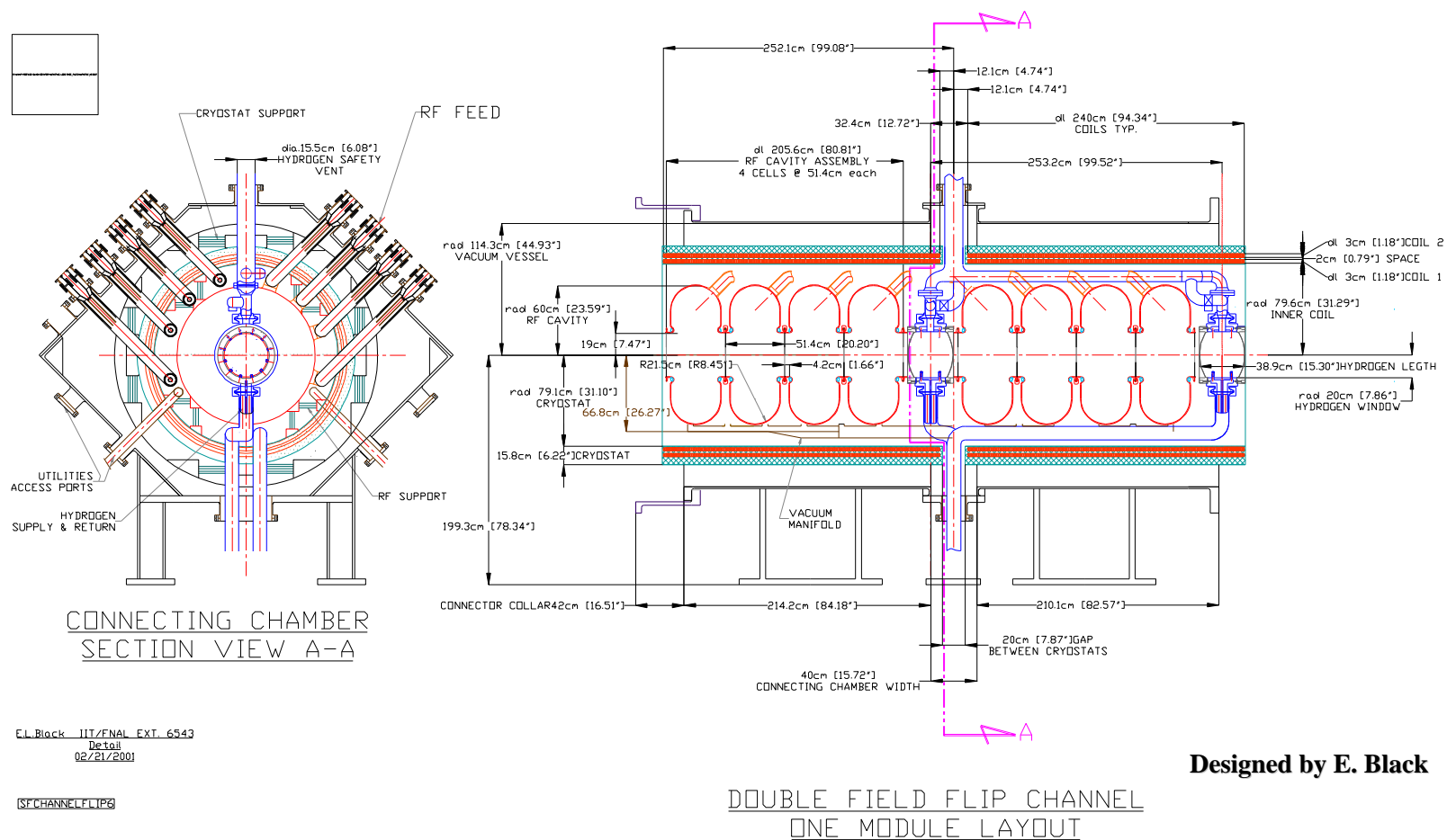
The **safety panel** requires a test up to the rupture point for at least one prototype in order to validate the design of the absorber window. The test can be at **room temperature**. The design will be validated if the predictions of the **Finite Element Analysis (FEA)** model agree with the test results. The calculation and **destruction** of the window will validate the **process of manufacturing** the windows in production.

Modules of the MUCOOL cooling channel

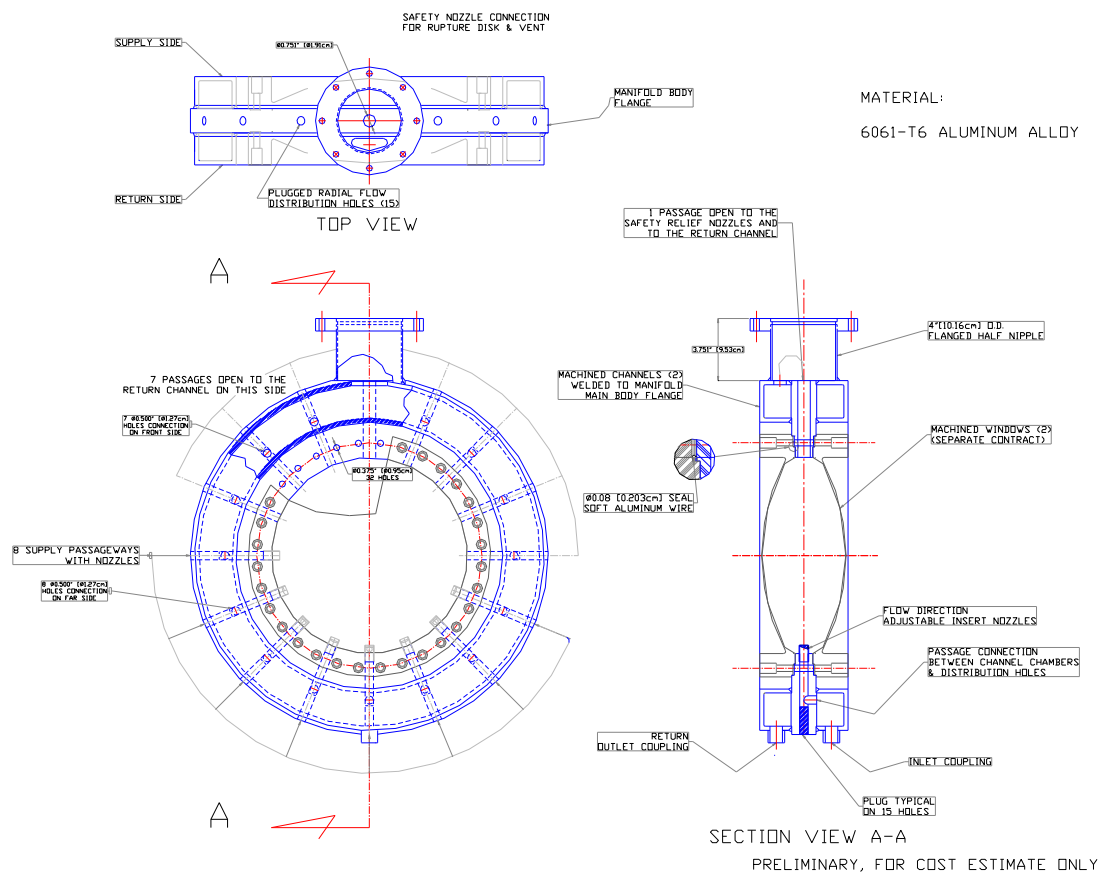
2 modules composing a portion of the 218 meters of cooling channel



Description of the MUCOOL experiment



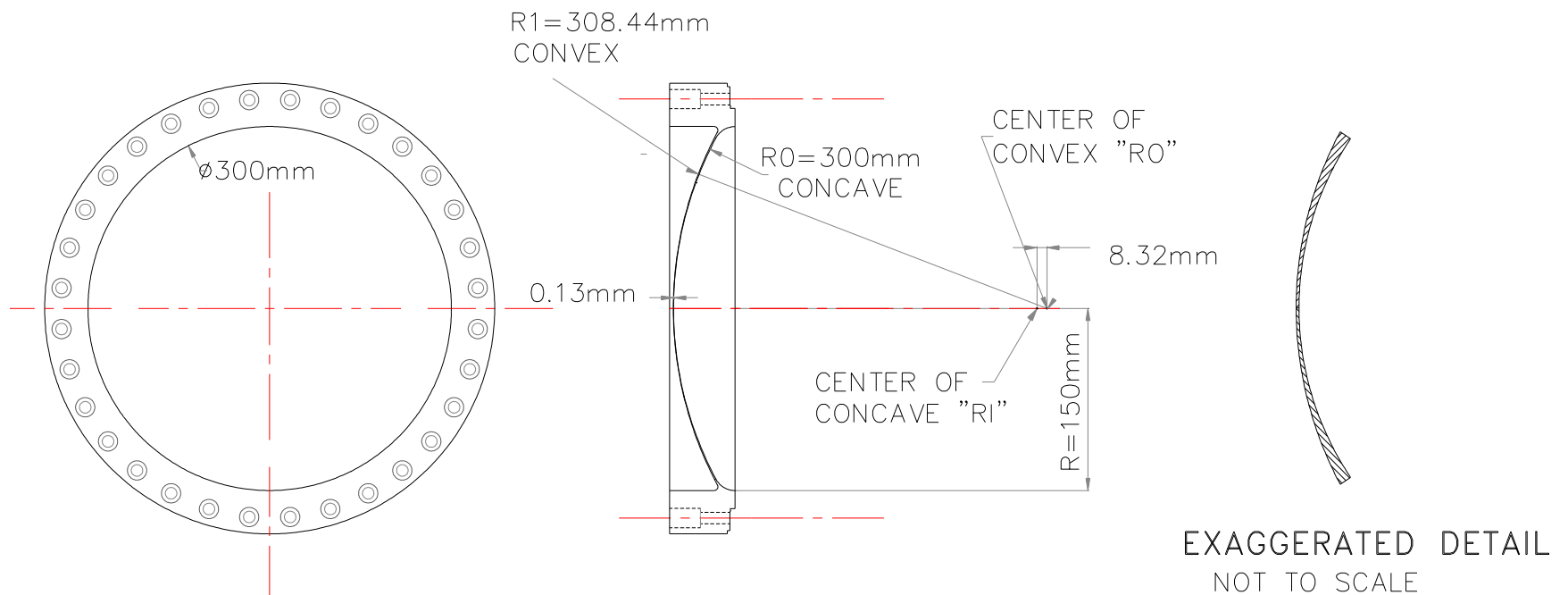
LH₂ absorber



ABSORBER MANIFOLD ASSEMBLY
 (Forced Flow Design)

Designed by E. Black

LH₂ absorber window



MATERIAL: 6061-T6 ALUMINUM ALLOY

Designed by E. Black

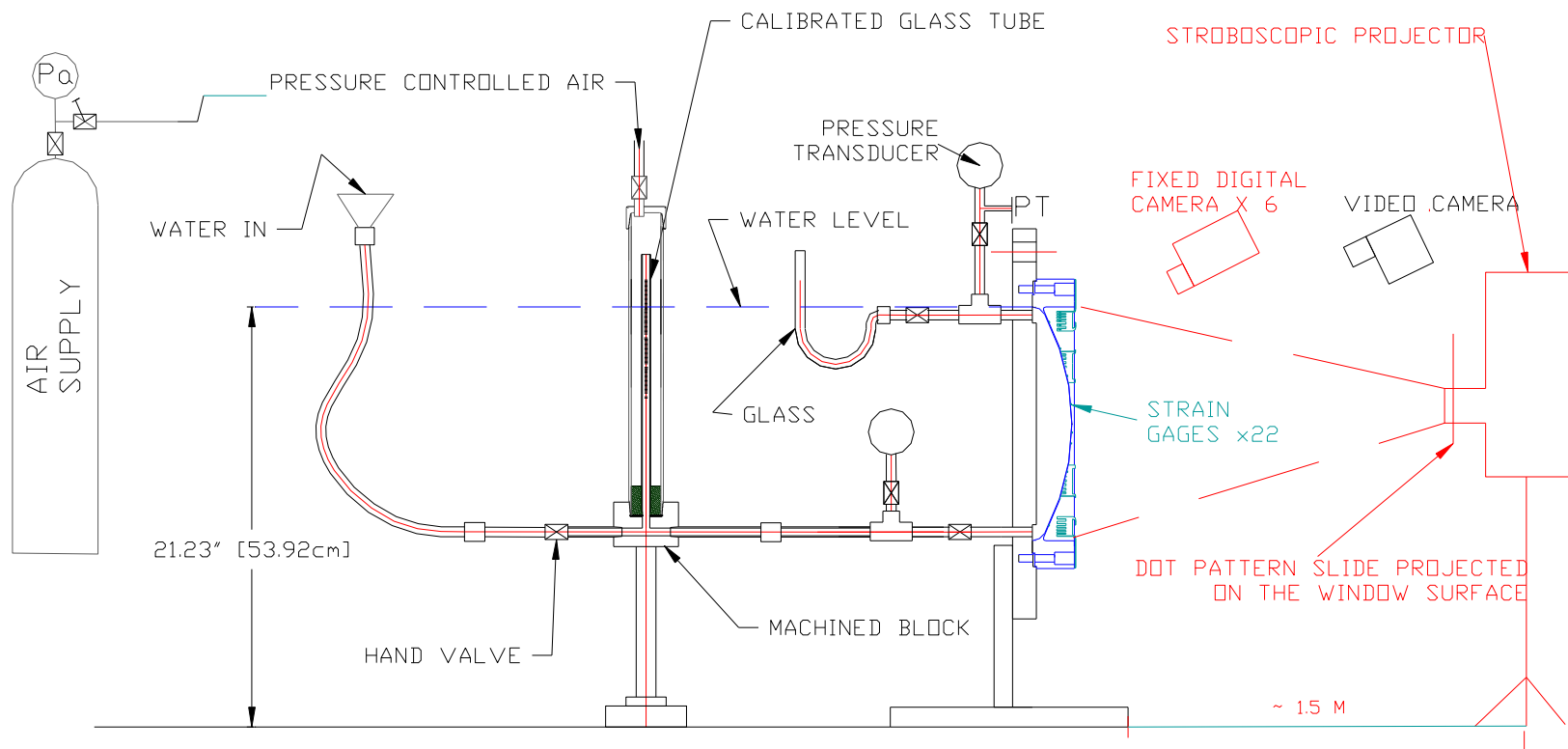
Goal of the pressure test

- ✧ Validate the Finite Element Analysis results
- ✧ Validate the design of the LH_2 absorber window
- ✧ To gain experience in the field of non-contact displacement measurements in order to foresee the future pressure tests.

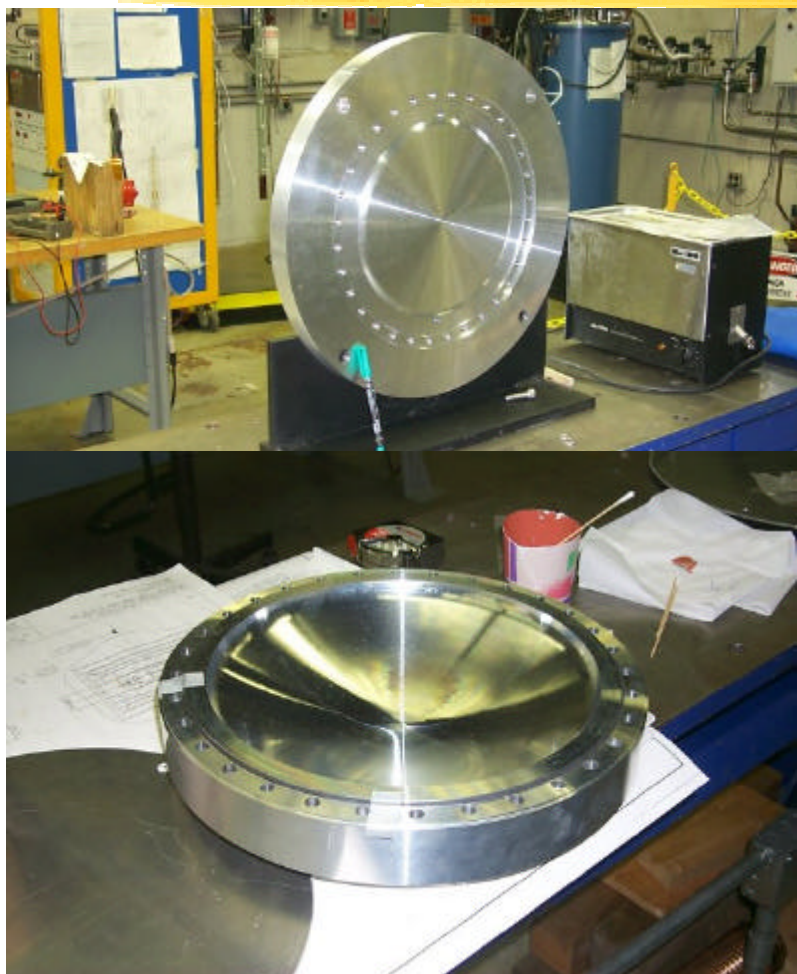
Characteristics of the test

- ➔ Prototype of a R15 cm LH_2 absorber window, 130 micron thick
- ➔ Test @ Room temperature
- ➔ Pressurization by water applied to the concave side of the window
- ➔ Measurement of the displacement => photogrammetry
- ➔ Measurement of the strain => Strain gages
- ➔ Measurement of the pressure applied to the window

Setup of the pressure test



Assembly of the absorber window



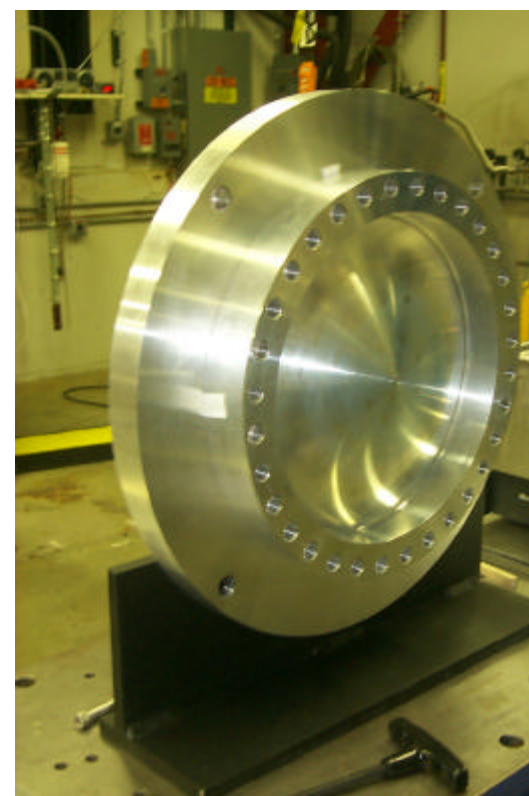
Back plane



**Assembly
of the
window on
its support**




**Window
concave
side up**

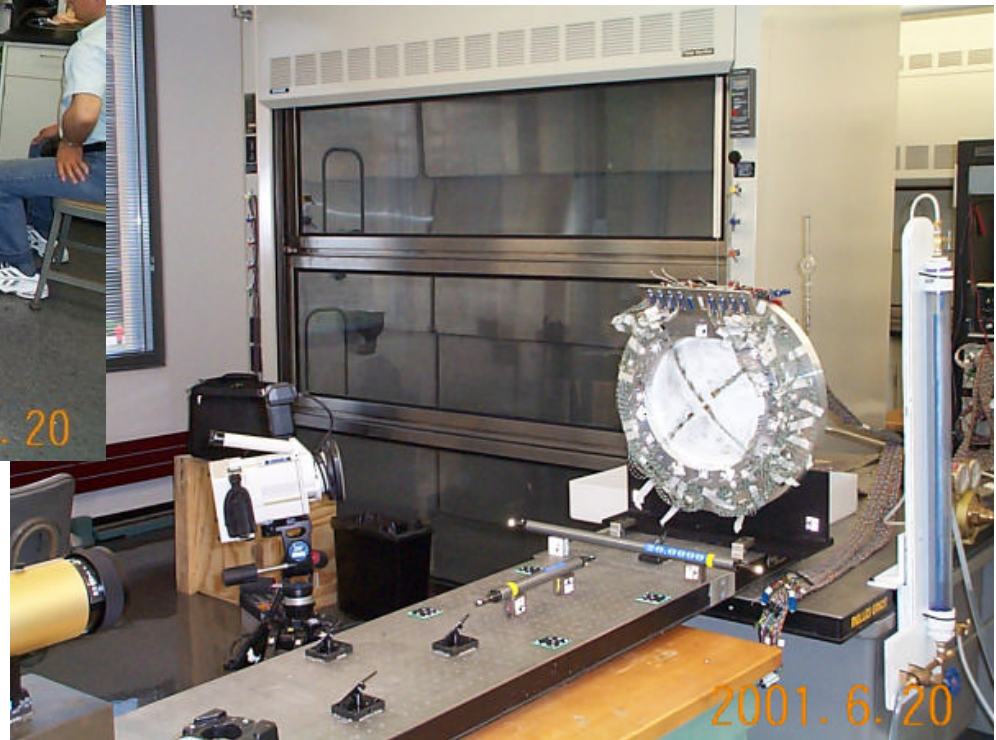


Preparation of the test at NIU




View of the window, video camera, digital camera and tripod and projector

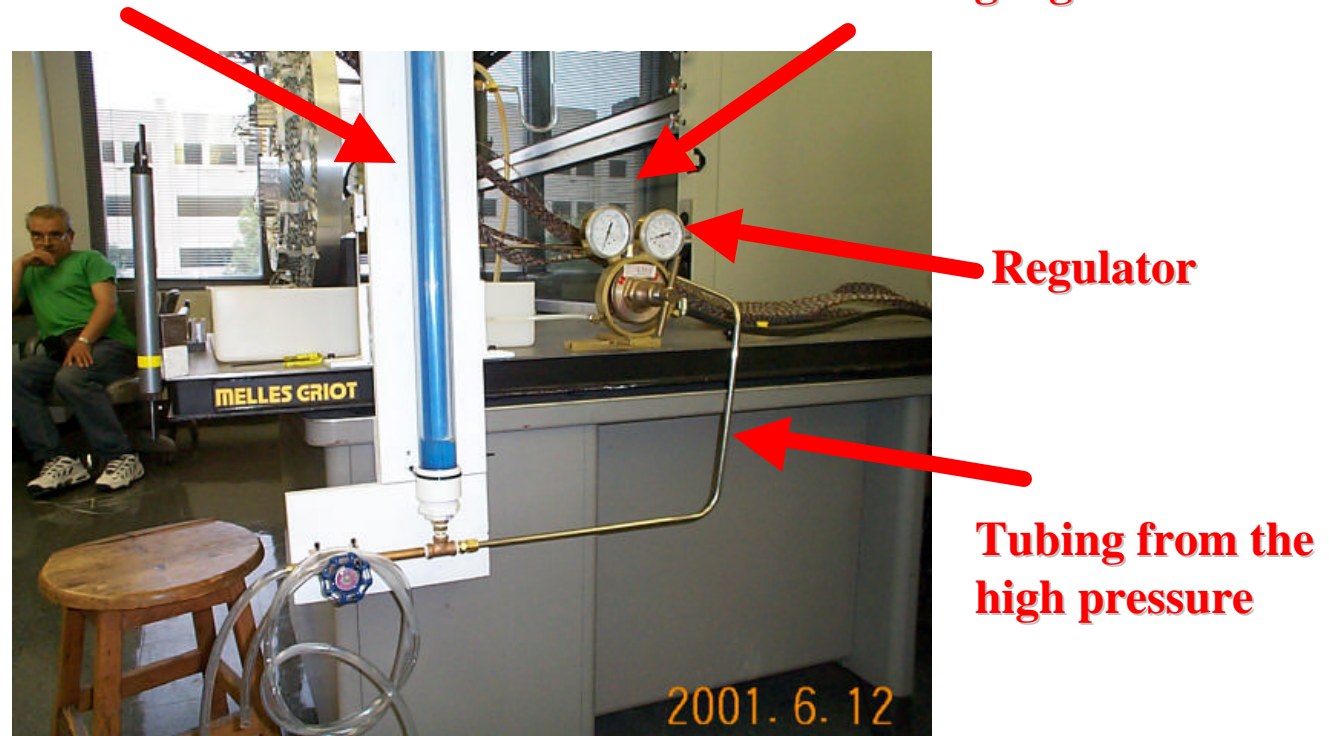
View of the window, scale bars and targeting sys.



Pressure circuit

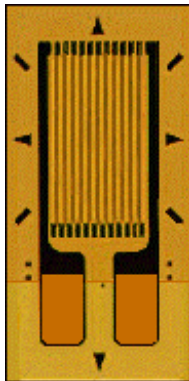
Graduated glass tube

Pressure gauges

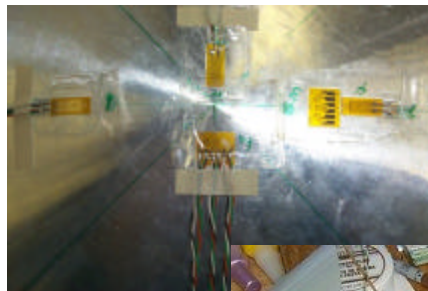
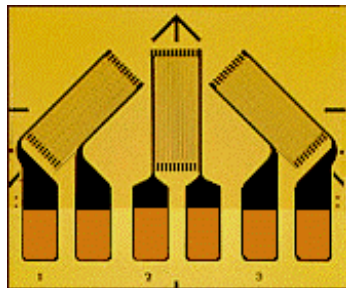


Instrumentation - strain gages

Unidirectional strain gages



Three-Element Rosette Pattern



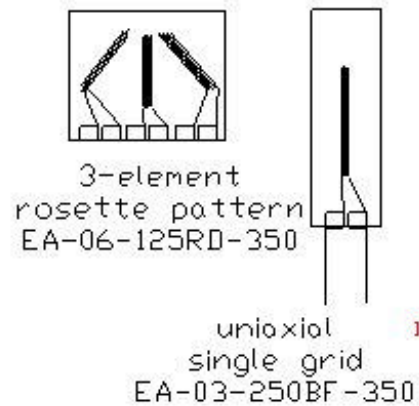
Preparation of the strain gages



Location of the strain gages

INSTALLATION OF THE STRAIN GAGES ON THE WINDOW

Strain gage types

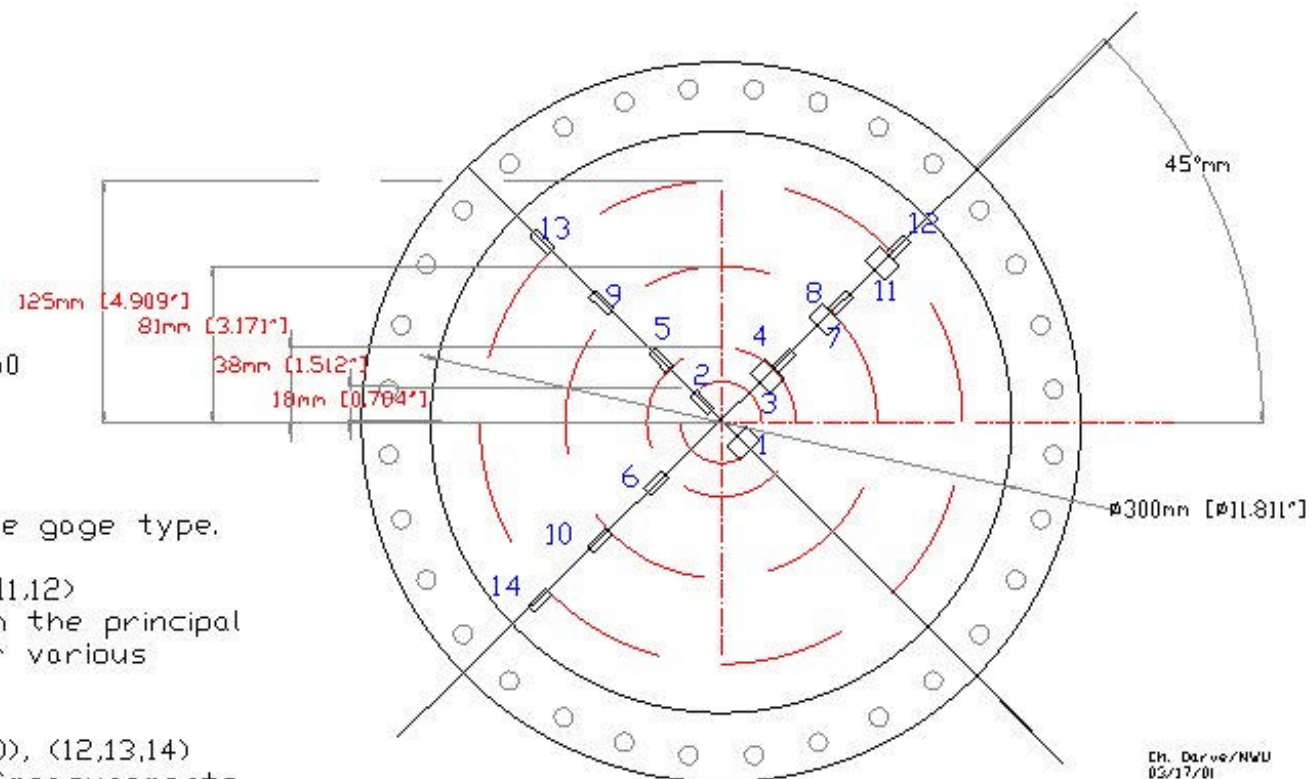


Purposes:

Gages (1,2)
 ==> influence of the gage type.

Gages (3,4), (7,8), (11,12)
 ==> correlation with the principal
 strain direction for various
 curvatures.

Gages (4,5,6), (8,9,10), (12,13,14)
 ==> Repeatability of measurements.

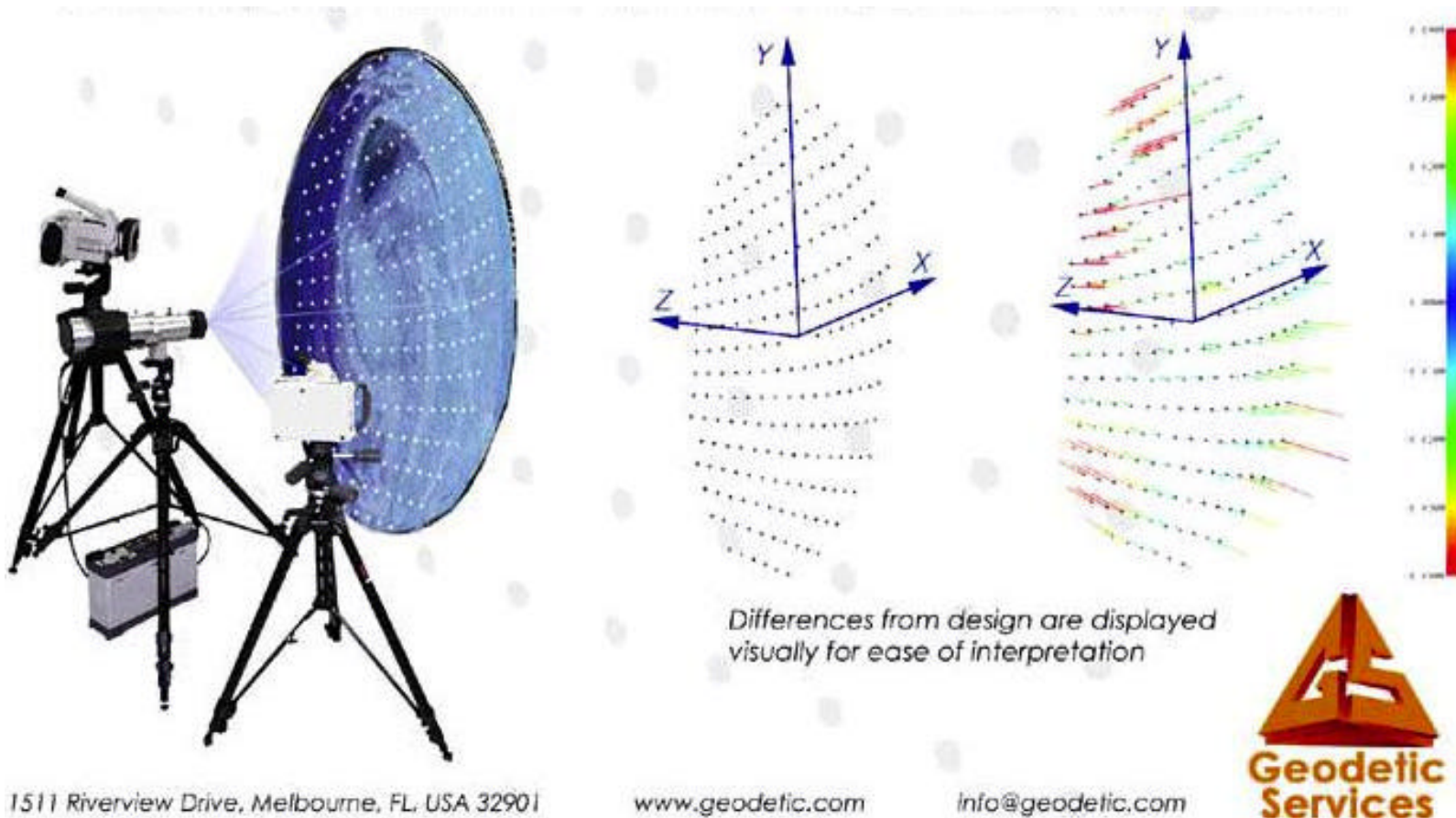


Displacement measurement strategy

The first strategy that came to mind was to place a series of adhesive strip targets along several radial lines on the convex surface. This was rejected for four reasons:

- 1) the window surface is so delicate that any unnecessary handling must be eliminated,
- 2) a number of strain gauges would be occupying part of the surface real estate,
- 3) the adhesive strips would actually act as support for the surface,
- 4) the strips, being a planar element, would cusp on a spherical surface, thereby causing irregular reflections from the targets on the strips.

Solution => Photogrammetry technique

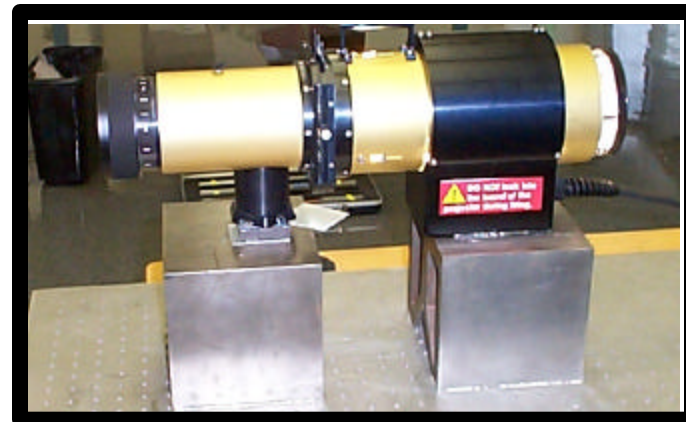


Stroboscopic Projector + slide



Specifications:

- ① Density of the dots: range from 650 to 5600 dots
- ① 0.2 mm dot size, 85 mm slide diameter
- ① wireless slave sync receiver to synchronize with the camera



Digital camera



Specifications:

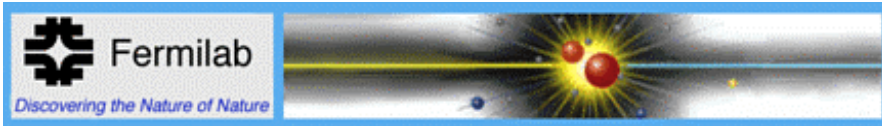
- ① 6.3 Megapixel
- ① 17 mm focal length lens
- ① 100 MHz onboard processor
- ① 850 MB disk drive

Video camera



Specifications:

- ① JCV GR-DV 31 Mini DV video cameras
- ① w/400x digital zoom



Principles:

- ① The target projector is strobed in synchronization with the camera
- ① The slide density chosen is 5,600 dots
- ① The 3 mm dots are projected to the window

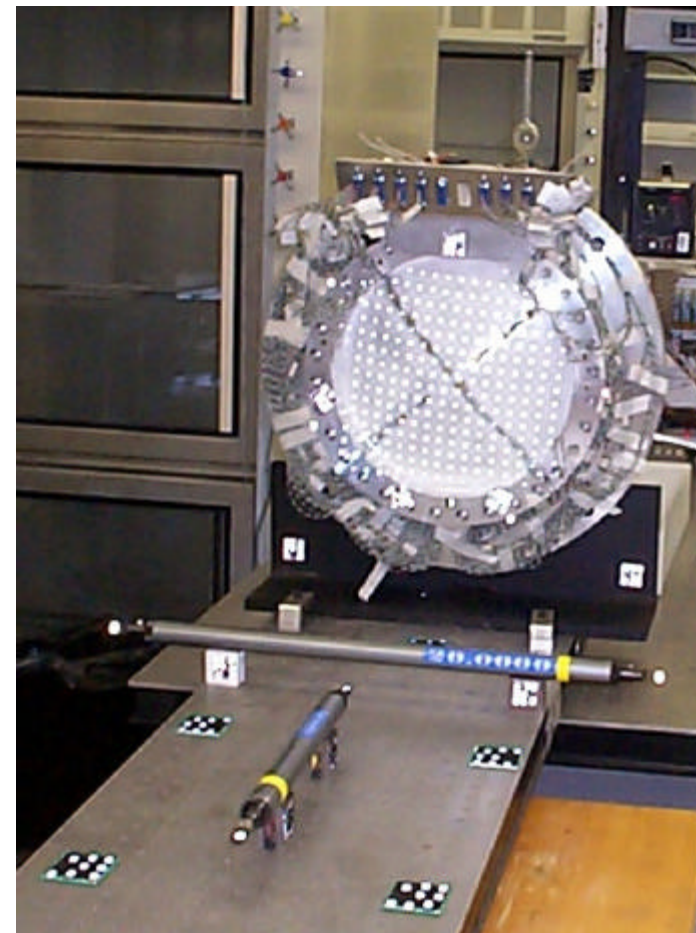
Keywords for the test description

- **Accurate**
- **Non-contacting**
- **Quick**
- **Reliable**
- **Ease of operation**
- **Compatibility for analyzing the FEA**
- **Complementary with other instrumentation**

View of the dots

**Dot pattern projected
on the window.**

**View of the targeting system
+ scale bars**



Photogrammetry measurements



**Six photos are taken
at various pressure stages**

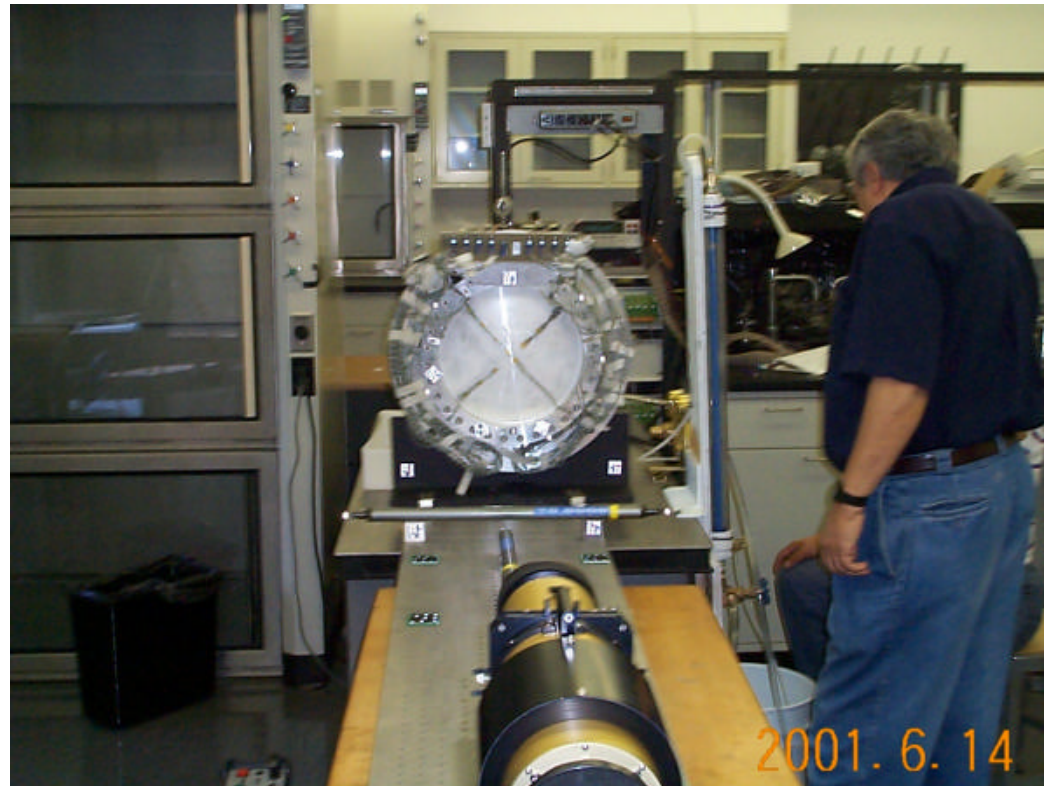


John with the digital camera

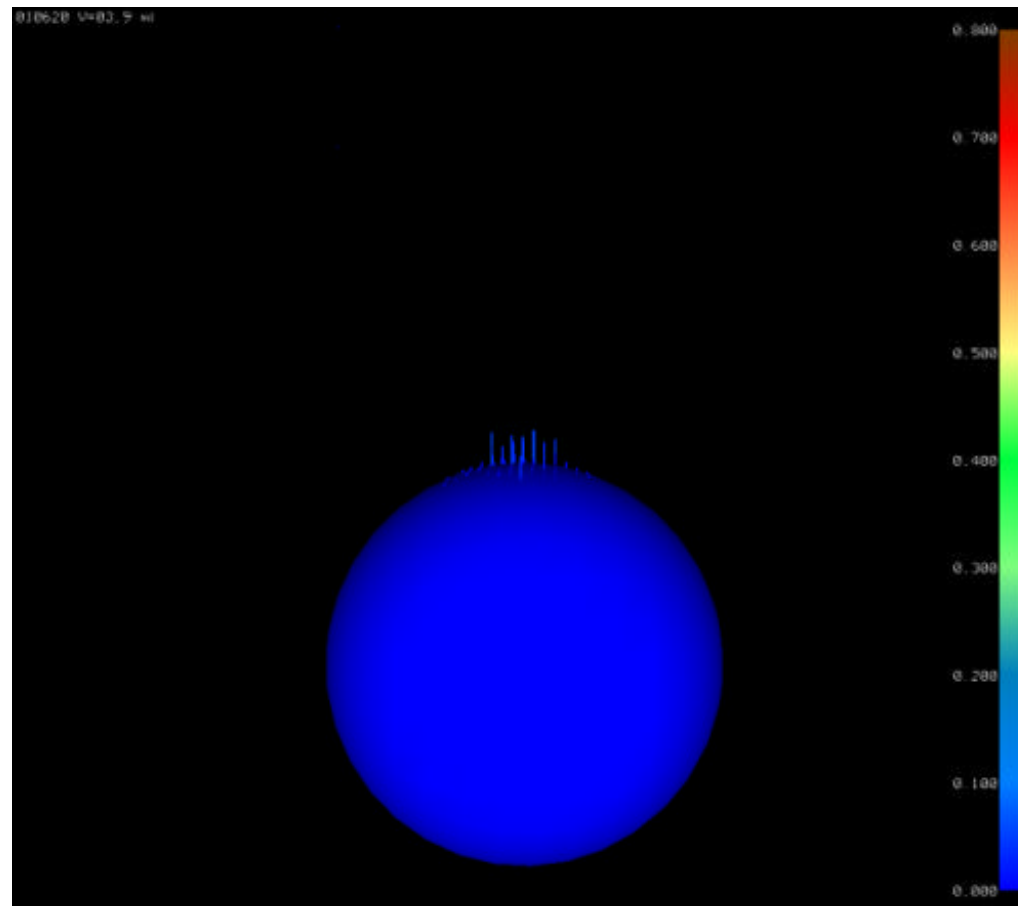


Photogrammetry measurements

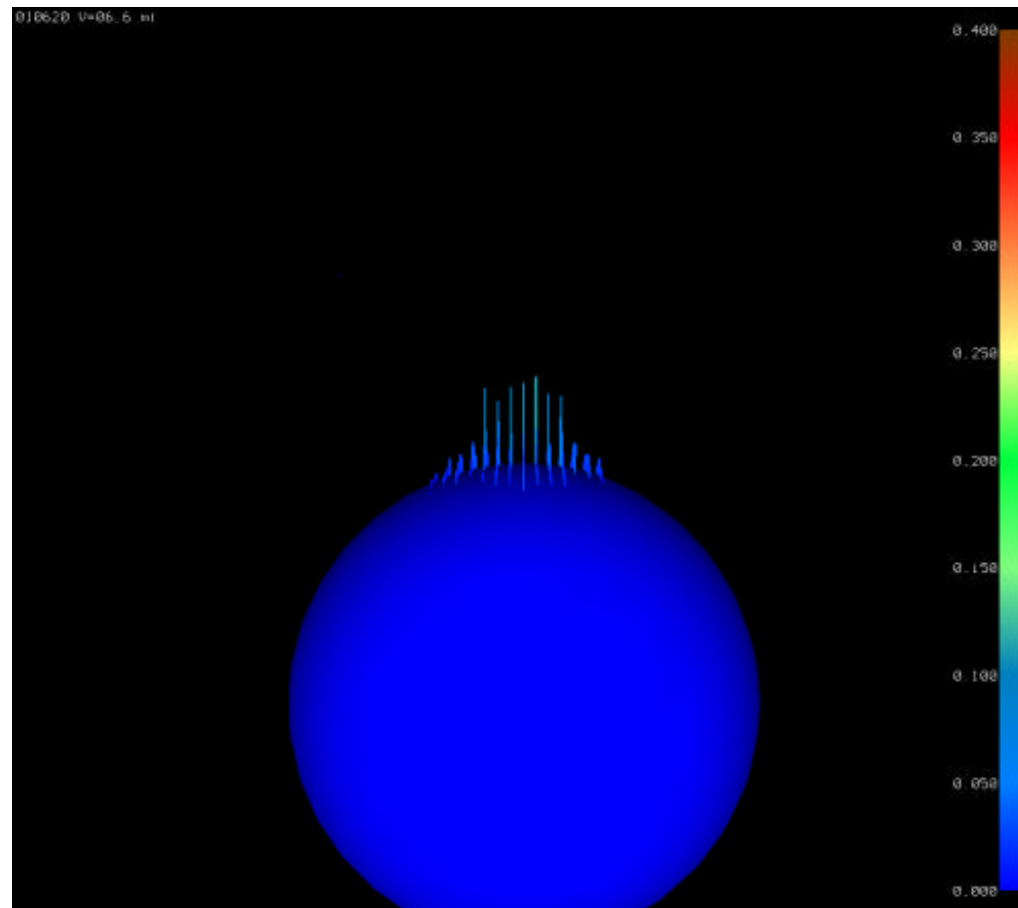
View of the window from the projector



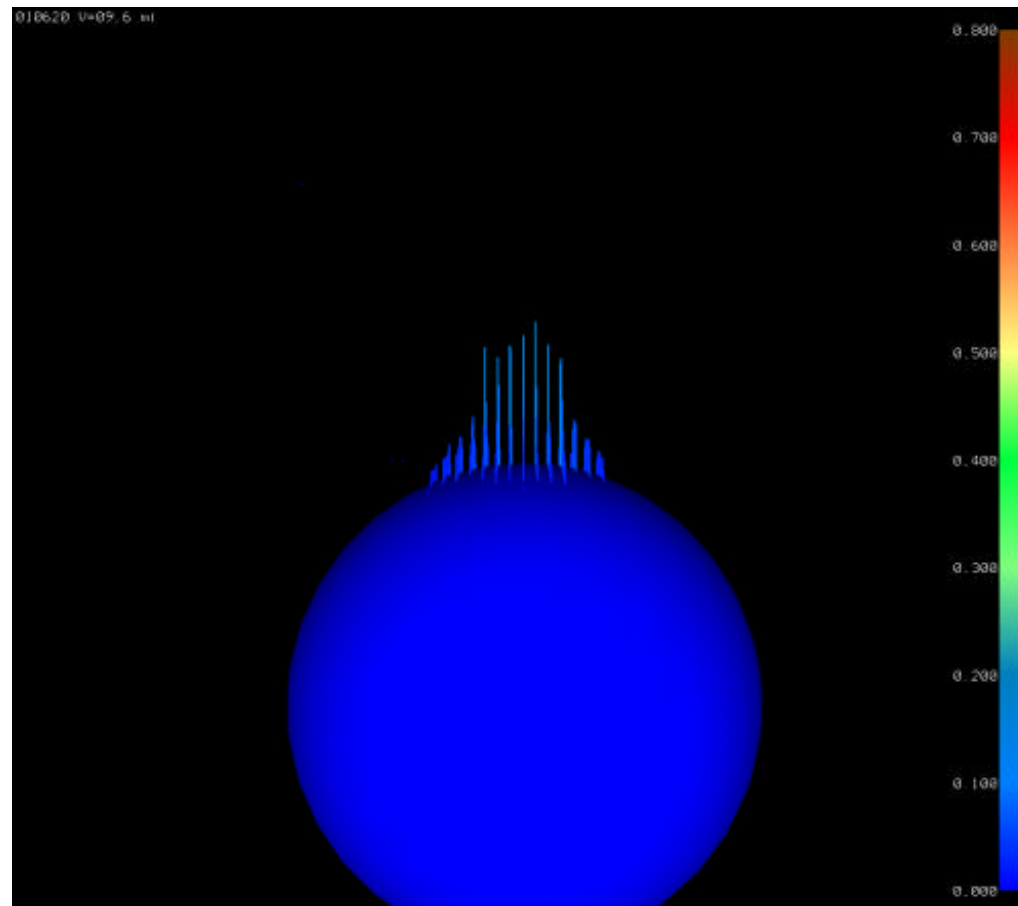
Photogrammetry Results - P= 2.5 PSIg



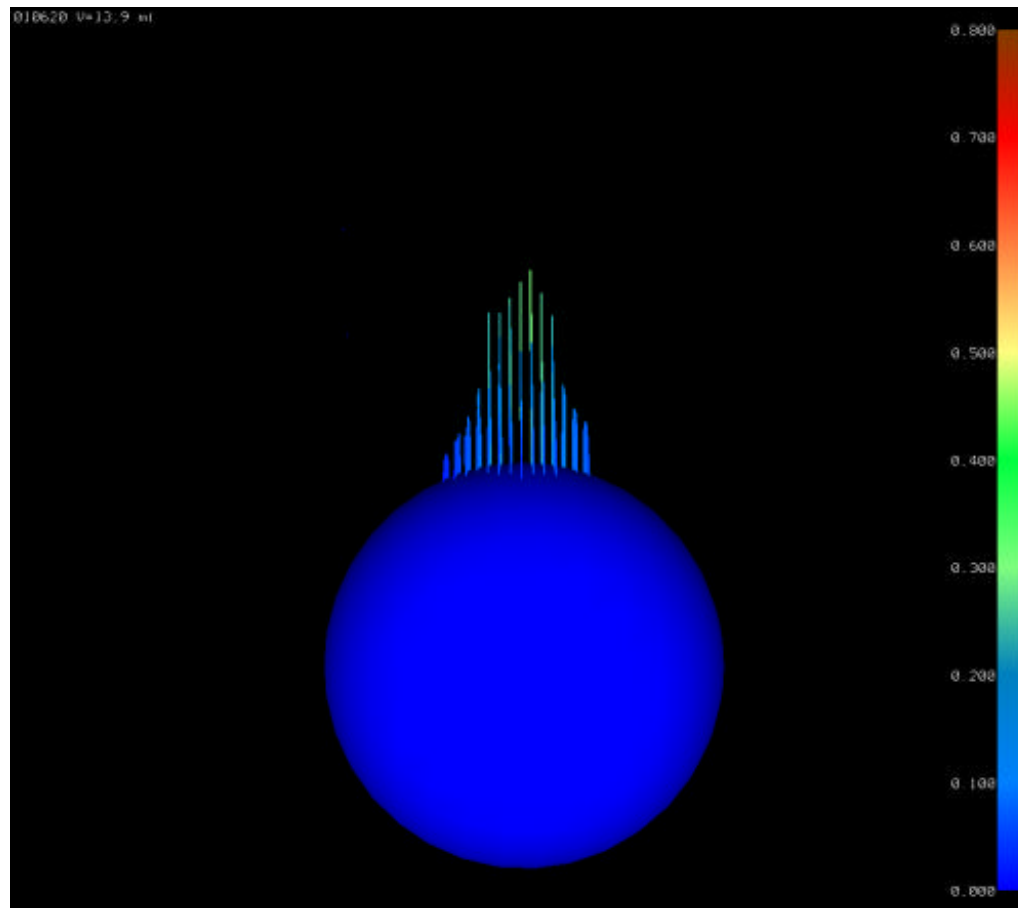
Results - P= 5 PSIg



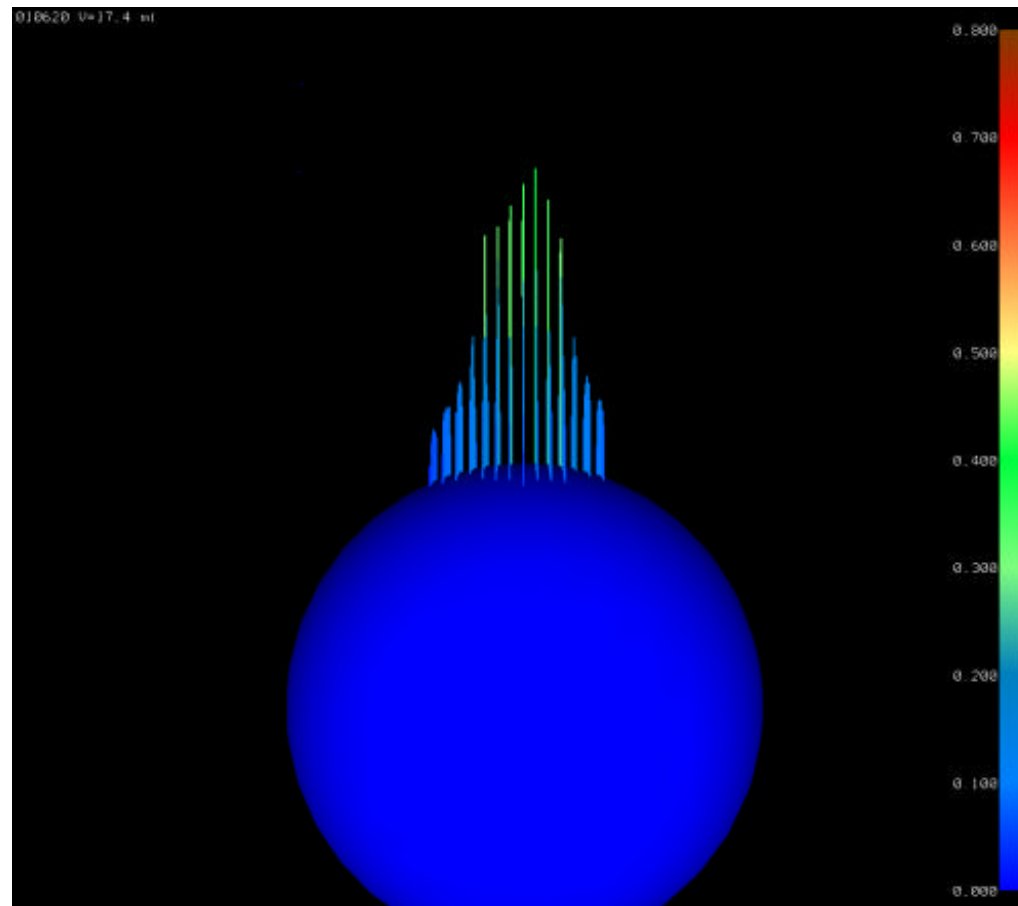
Results - P= 8 PSIg



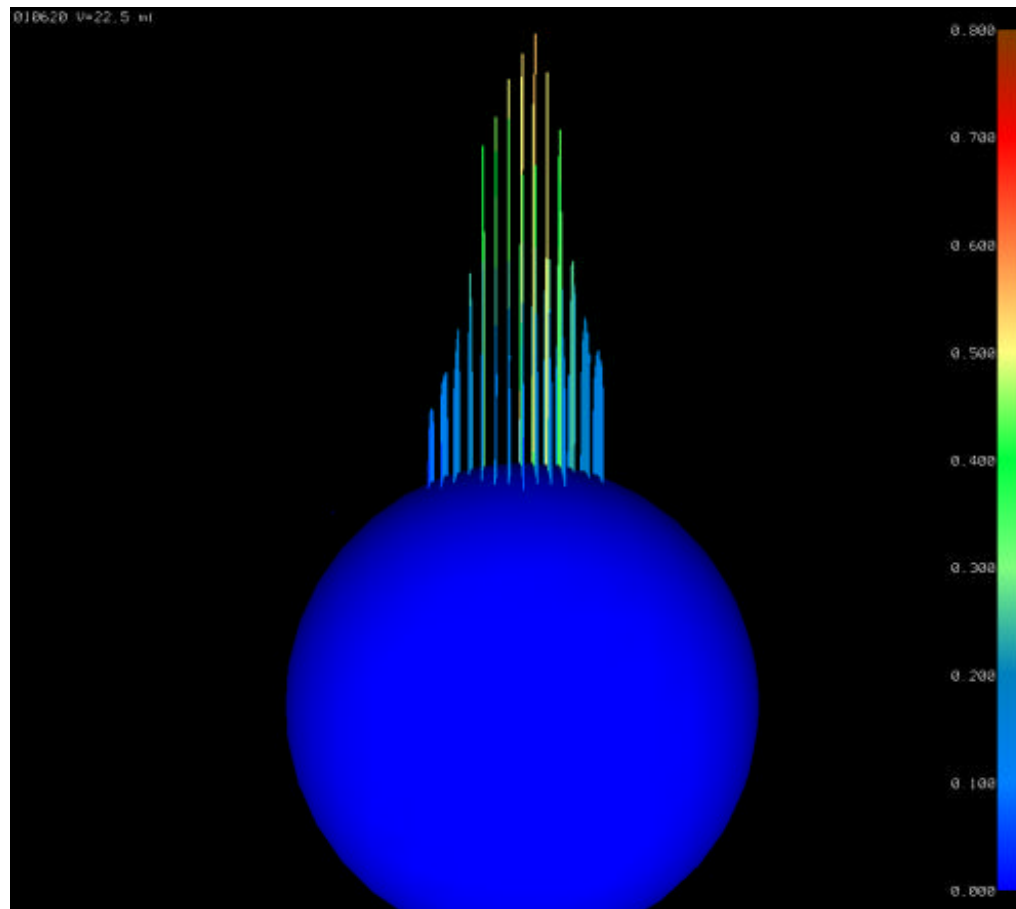
Results - $P = 13$ PSIG



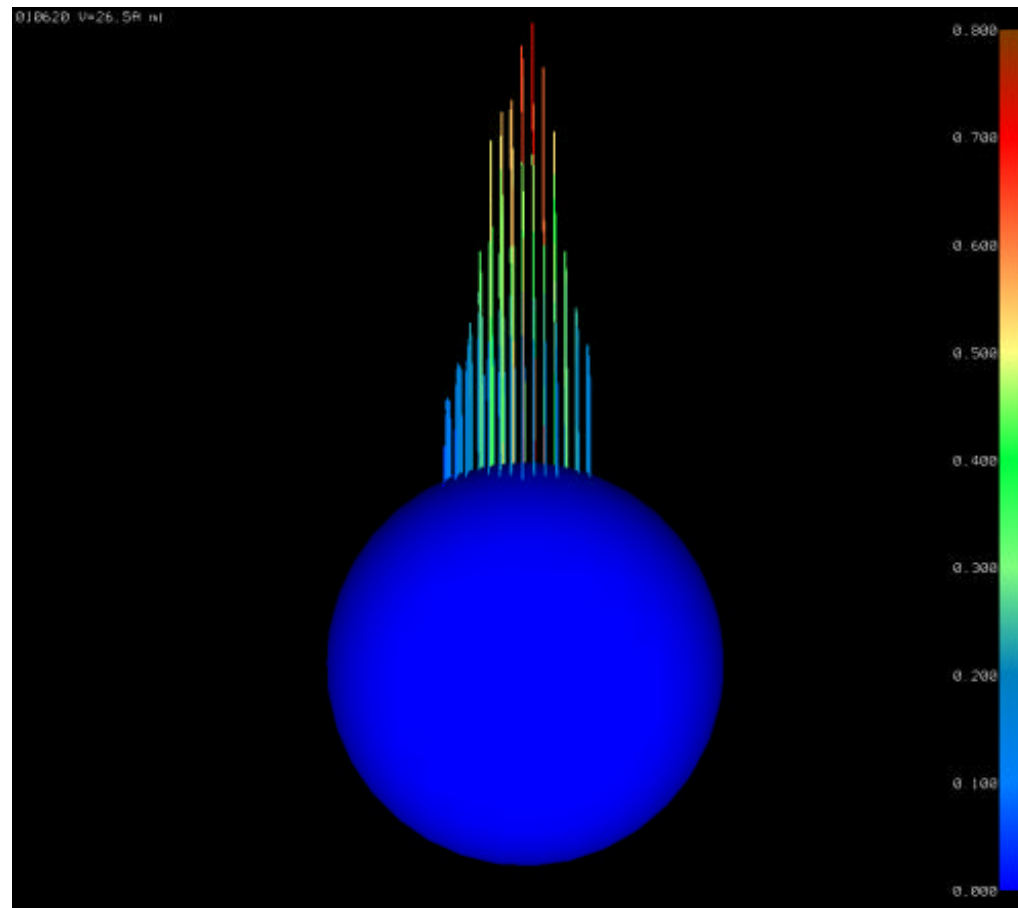
Results - $P = 17 \text{ PSIg}$



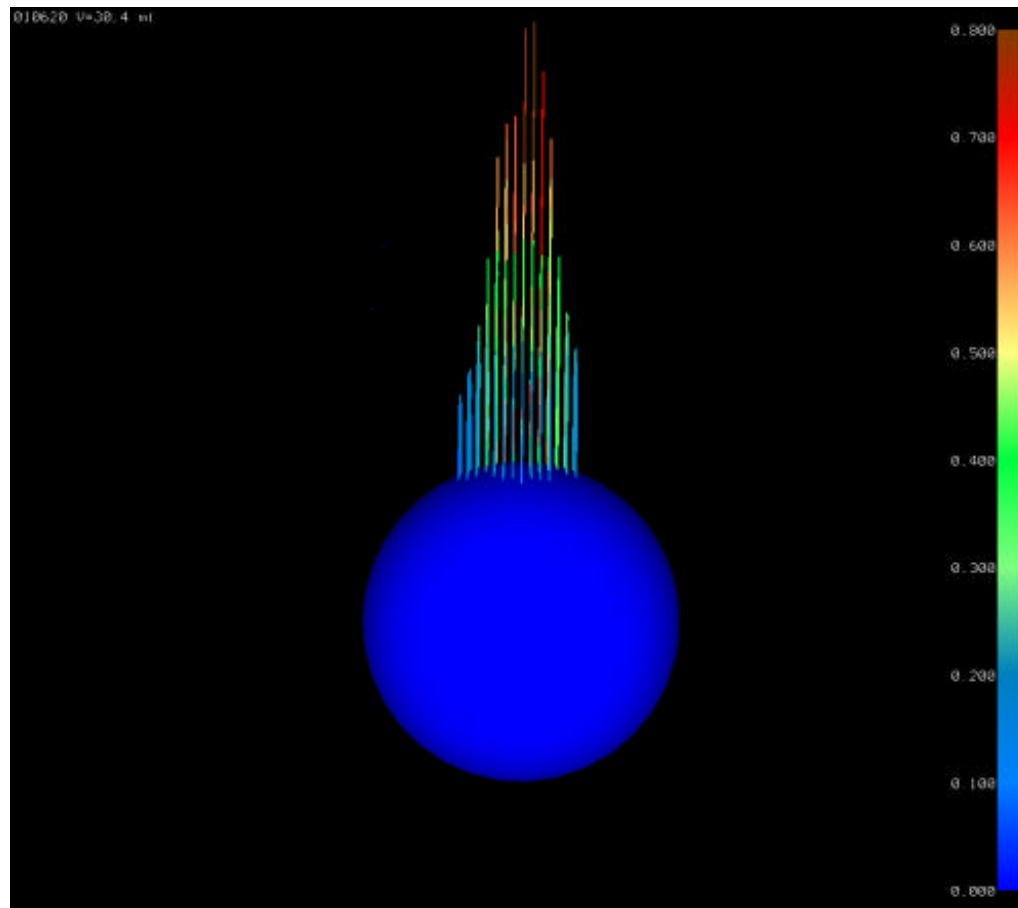
Results - P= 25 PSIg



Results - P= 31 PSIg



Results - P= 36 PSIg



Results - Finite Element Analysis

Goal:

Model the behavior of the absorber window for the process of acceptance of the manufacture of a series of windows

Procedure:

1- Calculations of the displacements, strains and stresses for the 0.13mm thick window while pressurized up at RT.

The measurements performed during the pressure test => validation of the FEA.

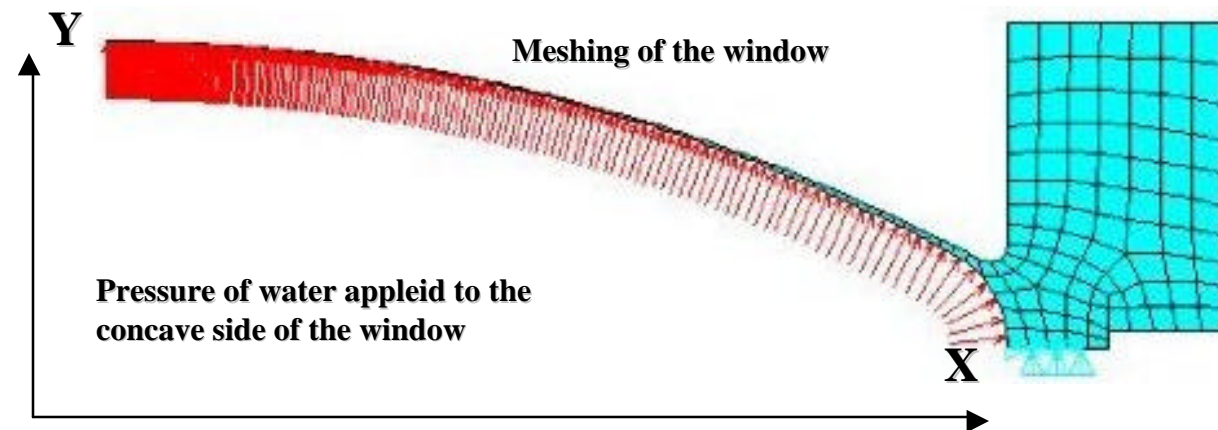
2- Calculations of the MUCOOL different configuration LH₂ absorber windows.

Note: Only the elastic mode of the materials is simulated=>safety interest

Results - Finite Element Analysis

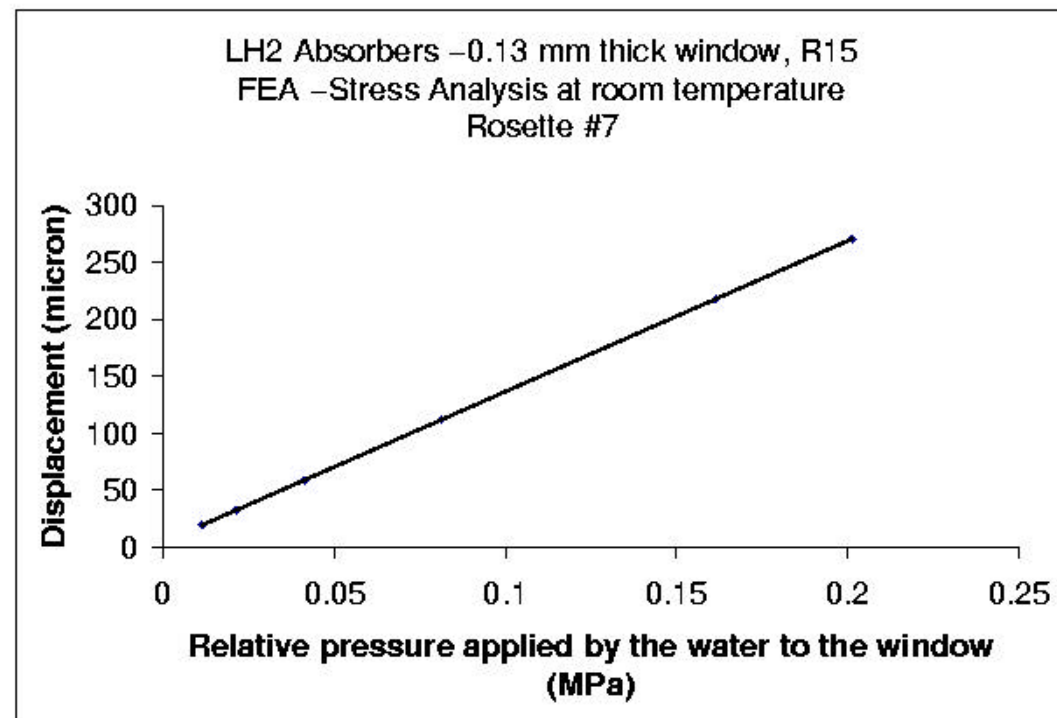
Definitions:

- Axisymmetric model
- Young's Modulus = 68.10^3 Mpa
- Poisson's coeff. = 0.3

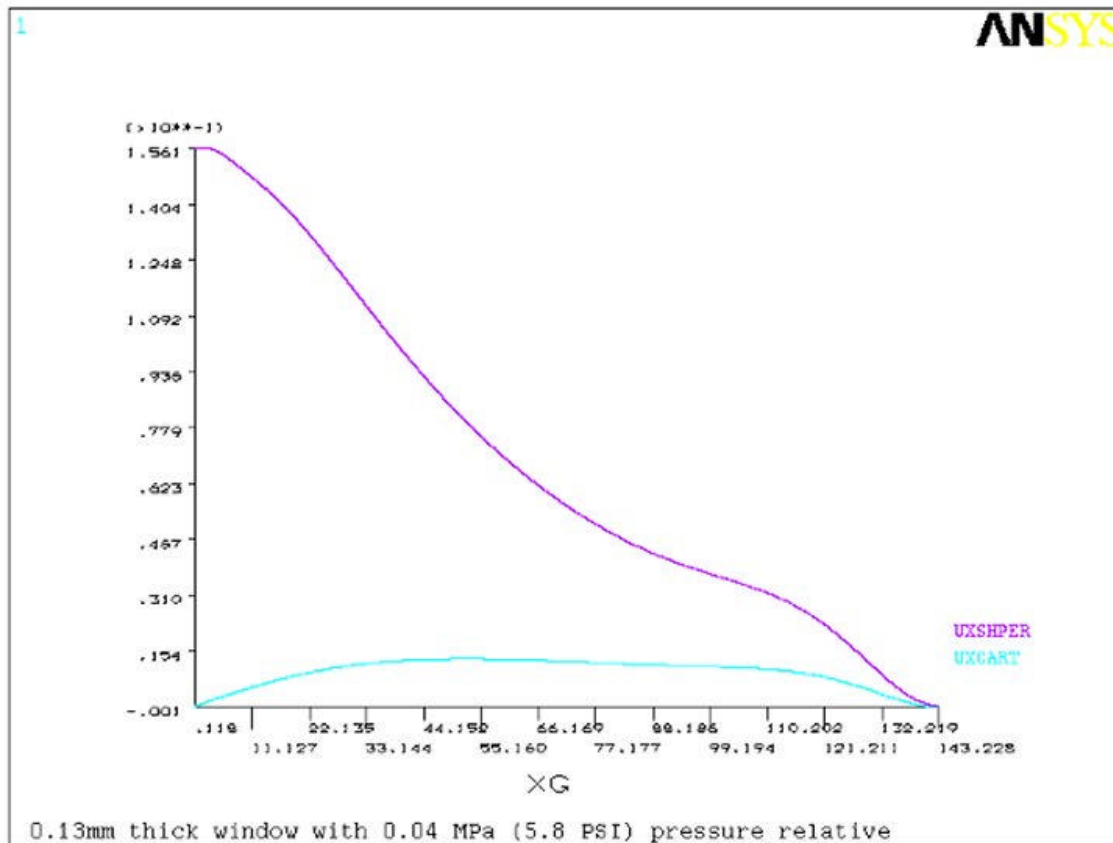


Results - Finite Element Analysis

Evolution of the displacement along Y-axis for a dot located at the position of strain gage # 7

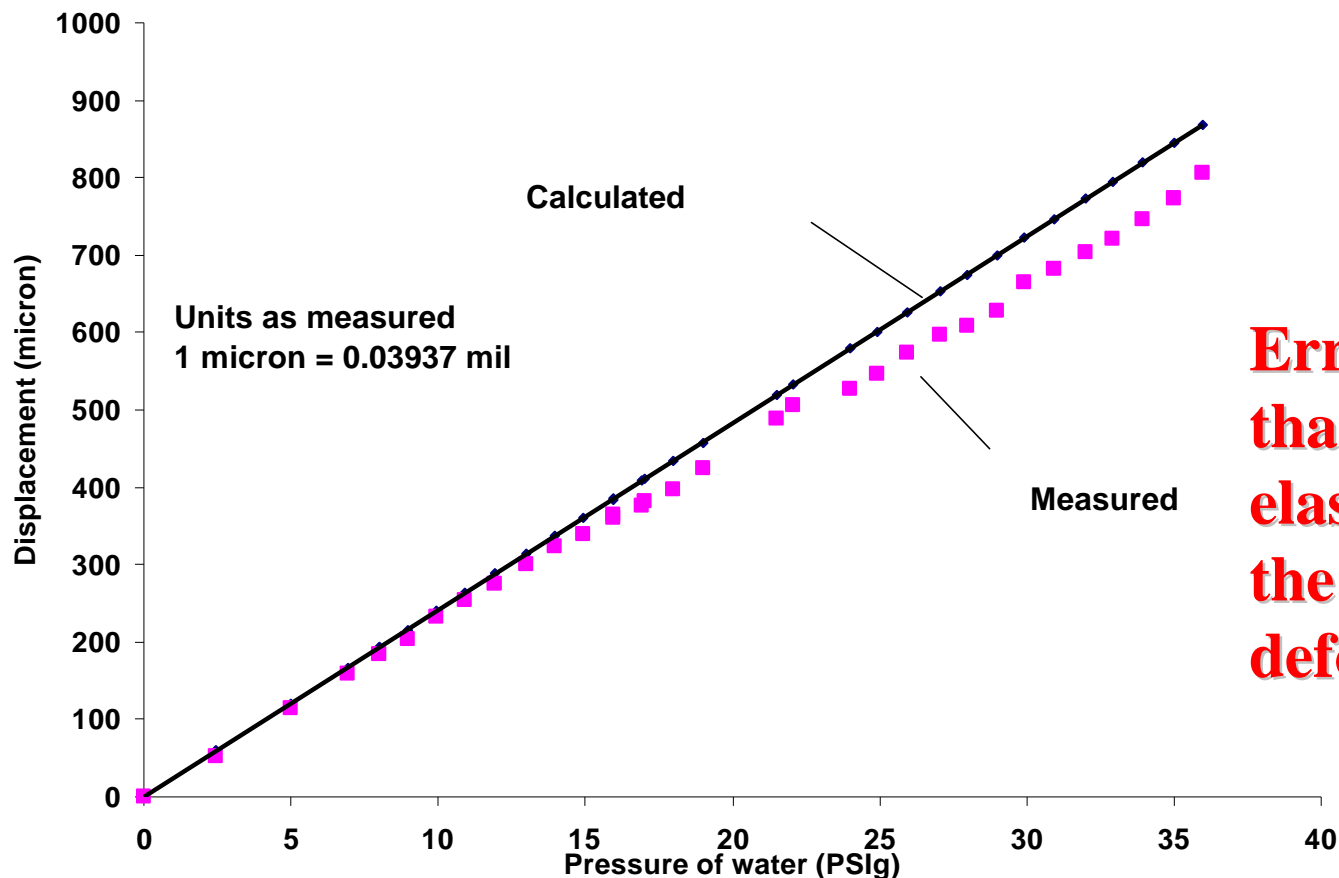


Results - Finite Element Analysis



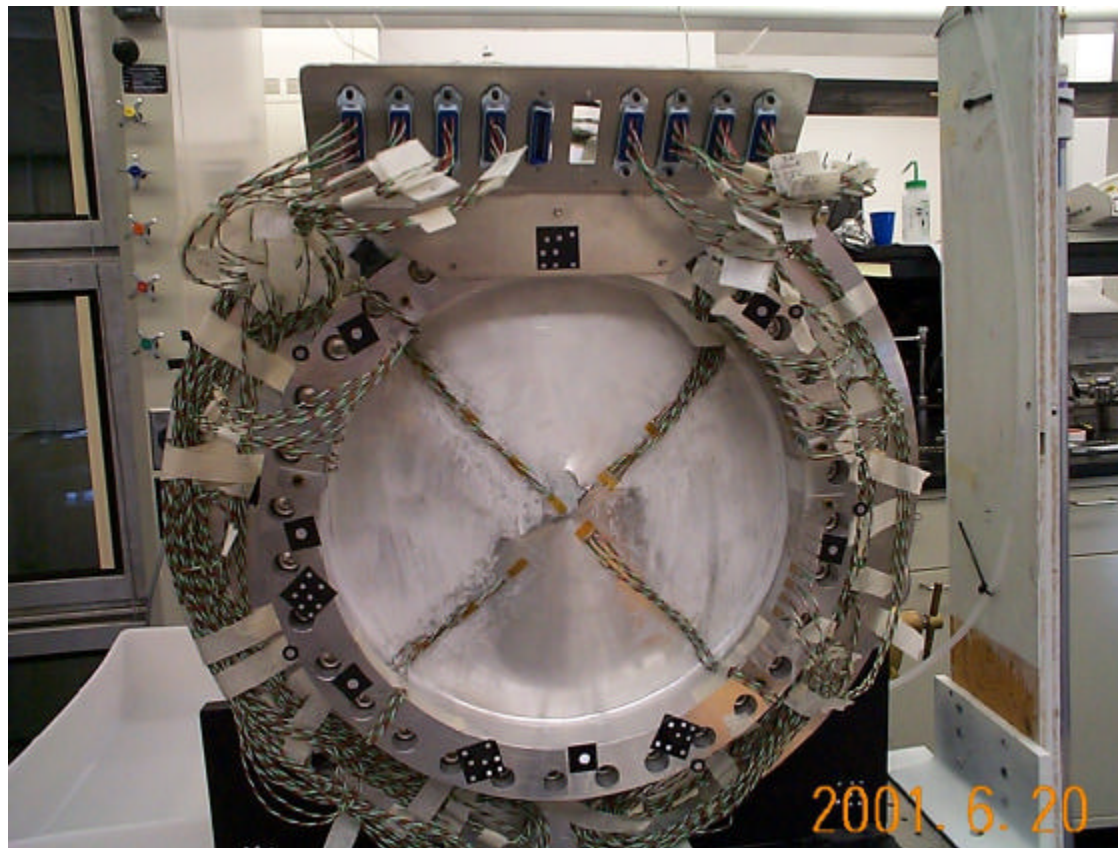
Distribution of the displacement along Y-axis for 0.04 MPa (5.8 PSIG)

Measurement and calculation comparison



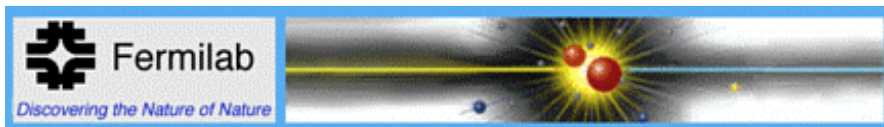
**Error smaller
than 6% in the
elastic mode of
the window
deformation**

Rupture @ 44 PSIg



Conclusions

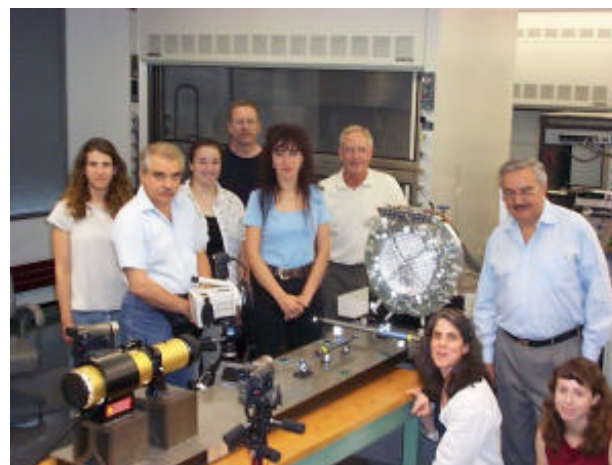
- ‡ The displacements determined using photogrammetry are in close correlation with the FEA predictions.
- ‡ Therefore, we validated the FEA and the LH₂ absorber window
- ‡ We destroyed the Absorber Window, as requested by the safety panel.
- ‡ The precision required (~0.010 mm) of the photogrammetry was achieved.
- ‡ The ability to acquire suitably accurate results in very short cycle-times was proven.



Acknowledgement

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At work



John Greenwood 14-17 August 2001

Failure-mode Metrology using Projected Target videogrammetry